



Opportunities in Mine Water Remediation: Leveraging Lessons and New Insights in Hydrogeology and Large Plume Treatment

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January 24, 2012,

About ARCADIS

- We provide consultancy, design, engineering and management services, with particular expertise in Water and Environment services
- 19,000 staff in Europe, South America (Brazil, Chile, Peru), Canada, and the US
- Our Mission is to improve the quality of life by creating innovative and enduring solutions that enhance the built and natural environments. By doing so, we produce exceptional value for our clients, employees, and shareholders.
- Our Values

Integrity

Client Driven

Agility

Collaboration

Entrepreneurship

Health & Safety



Mining-Related Services and Capabilities

- Water supply & storage
- Mine water flooding and dewatering
- Water management modeling
- Pit lake management
- Surface water quality
- Stormwater management
- Groundwater plume treatment
- Environmental risk assessment
- Impoundment design
- Slope stabilization
- Geotechnical services



- Demolition and reclamation
- Mine Permitting and Planning
- Heap leach evaluations/optimization
- In-situ mineral extraction

Problem and Opportunity

- Many mine sites have very large groundwater plumes (sulfate, selenium, arsenic, uranium, etc.)
- Conventional approaches are often containment-based: *No end in sight*
- Experience and new technical developments makes large plume treatment feasible and cost effective



- *Leveraging these advances in plume treatment strategies will result in near-term progress, lifecycle cost certainty, and reduced risk*

Examples: Large Uranium and Sulfate Plumes



Goal

Protect the environment in a manner that is equitable, requires a reasonable level of short-term stewardship, provides a meaningful near-term risk reduction, is sustainable beyond the timeframe of active intervention, and represents a low risk of failure.



Three Key Elements to Successful Approach

1. Founded on remediation-scale hydrogeology

- Improved understanding of contaminant transport
- More successful remediation performance

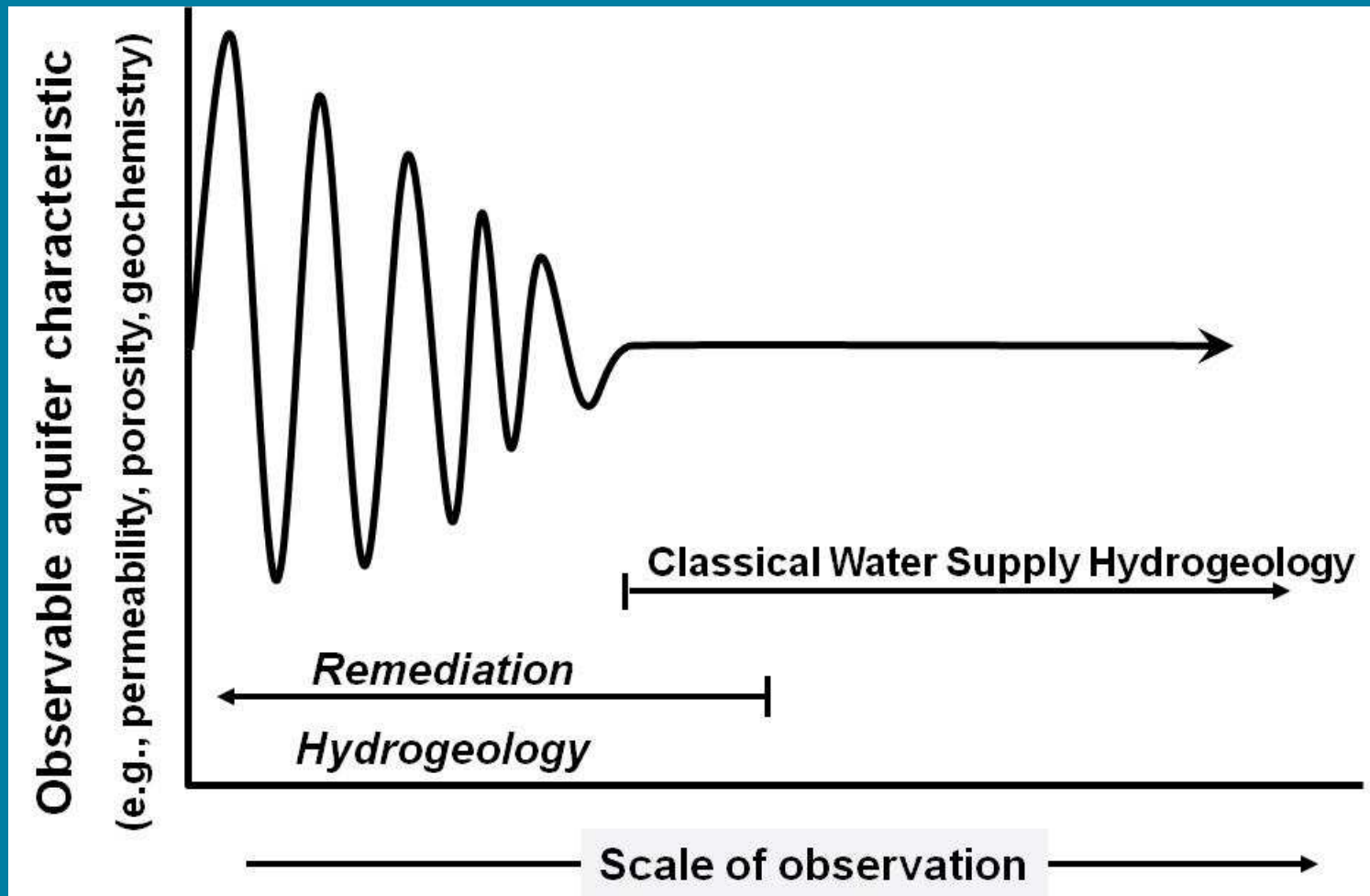
2. Incorporate in situ treatment approaches

- Implementation experience well-developed for large plumes
- New technologies applicable for mining-related constituents

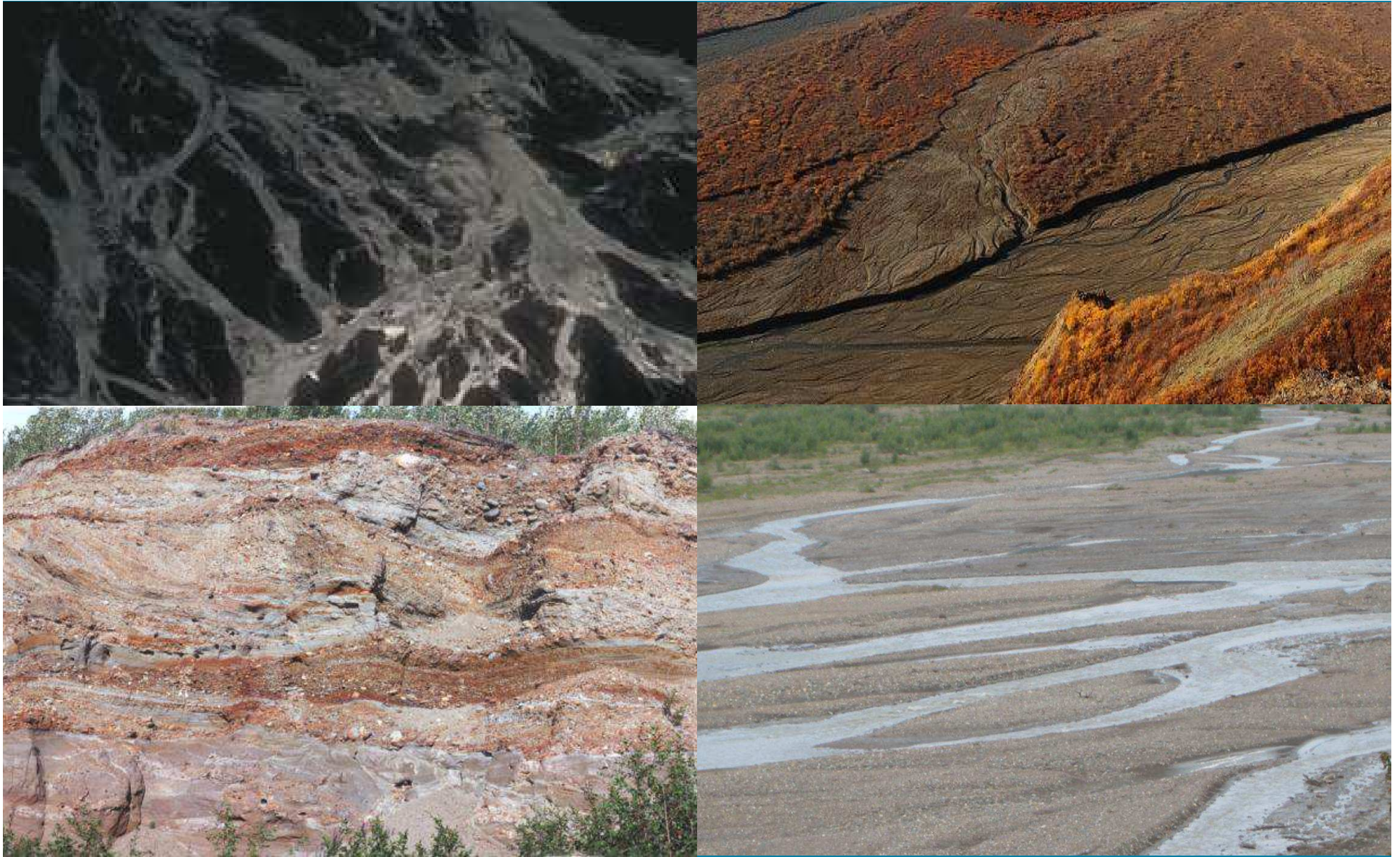
3. Holistic and flux-focused

- The “Hii” Road: An integrative, prioritized, and adaptive strategy
- Greatest near-term benefit and overall return on investment

The Remediation Hydrogeology Domain



Aquifers are Heterogeneous!



Most of the flow and transport
(mobile porosity)

Most of the storage
(immobile porosity)

10^{-2} cm/sec

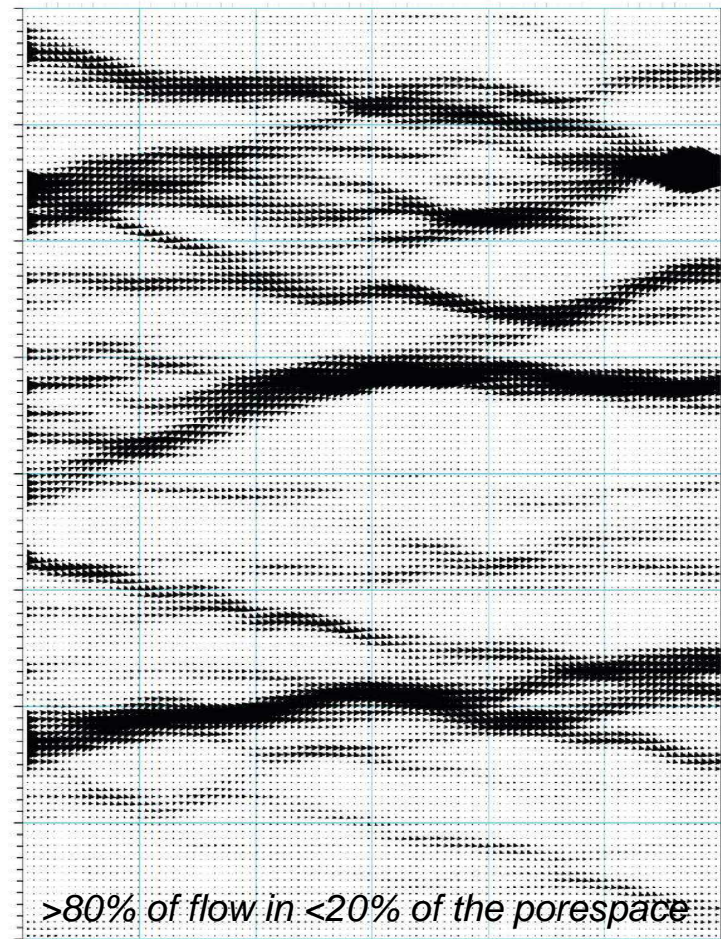
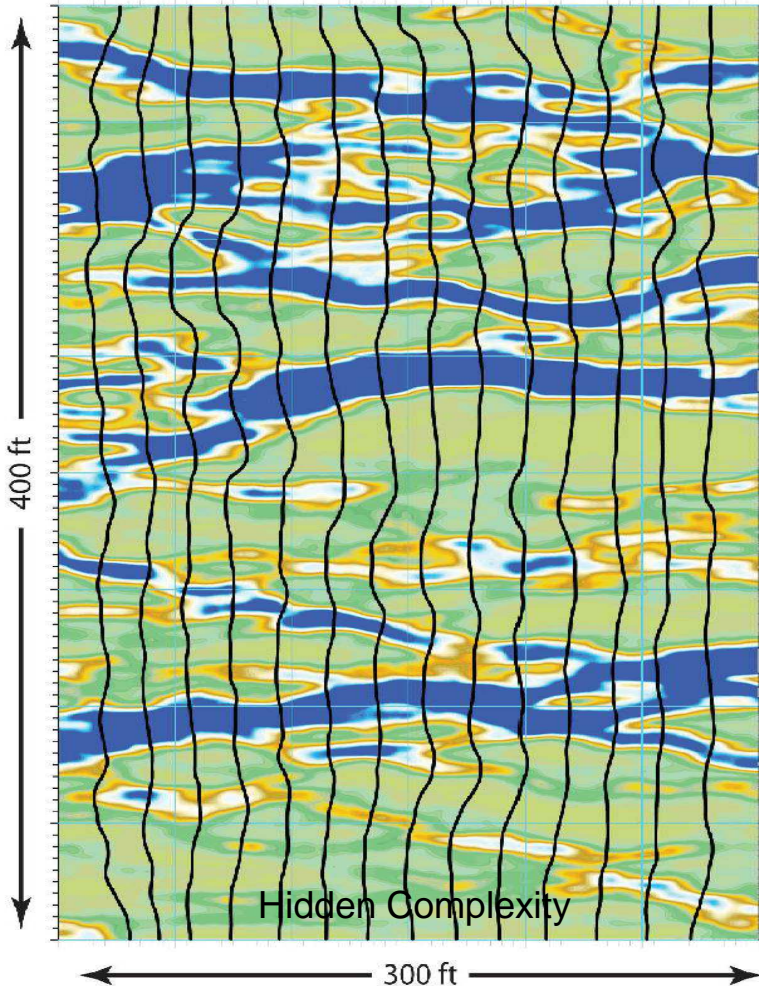
10^{-6} cm/sec

10^{-4} cm/sec

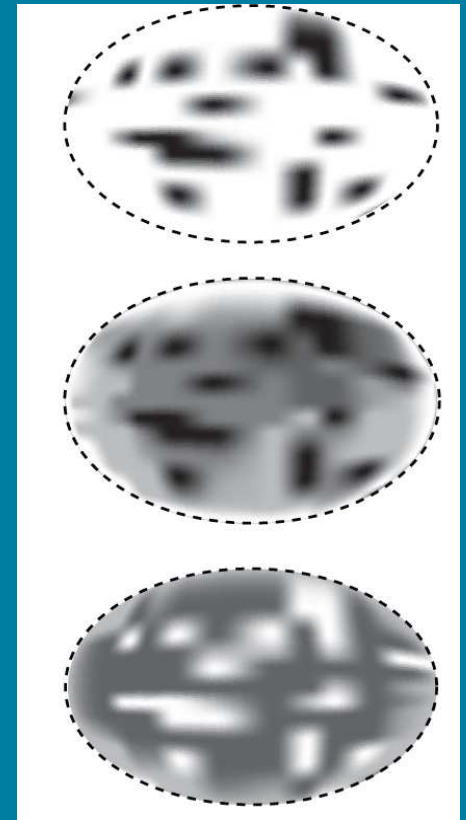
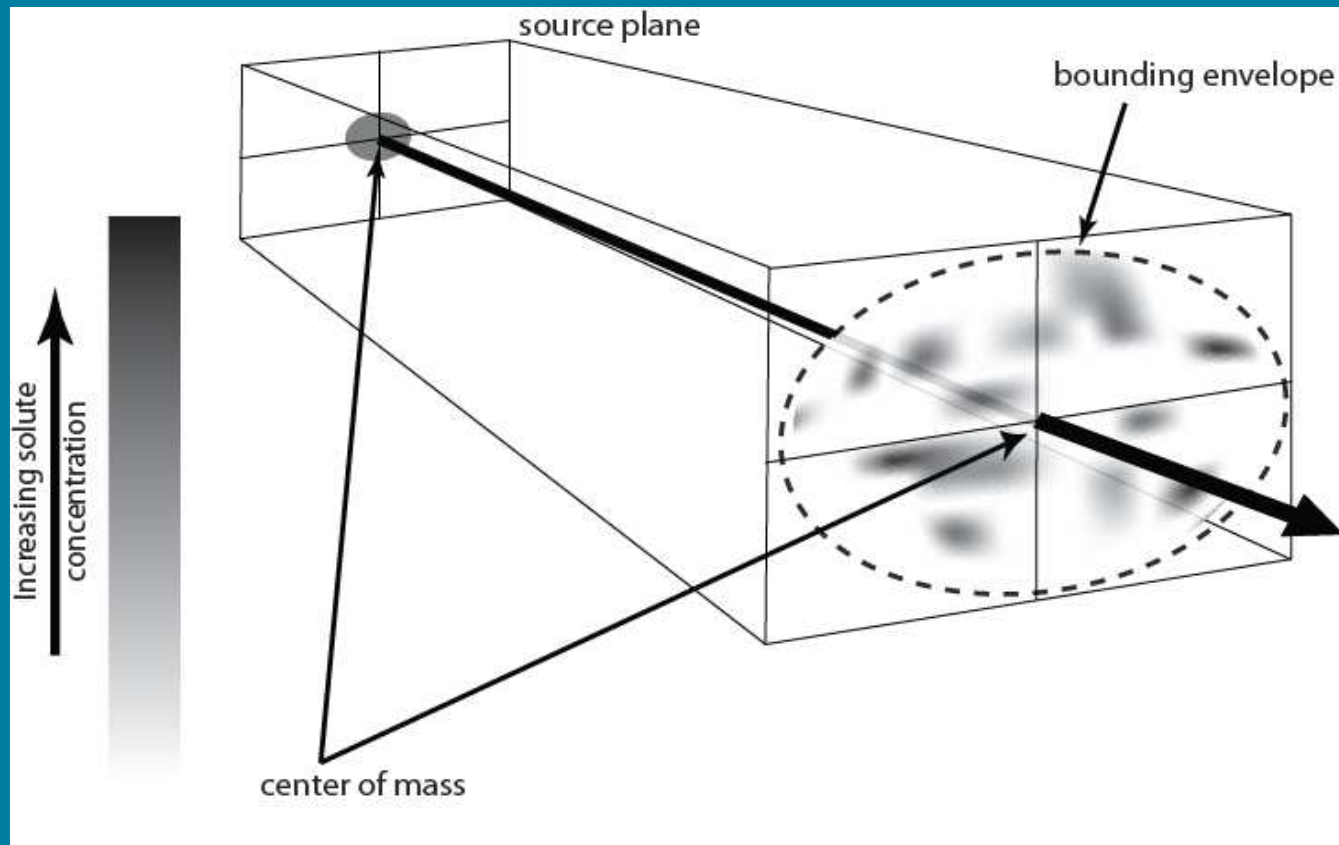


inches

Flow Focusing



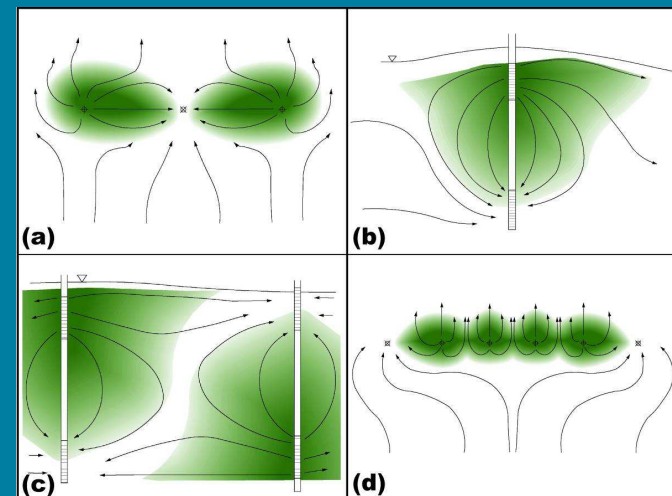
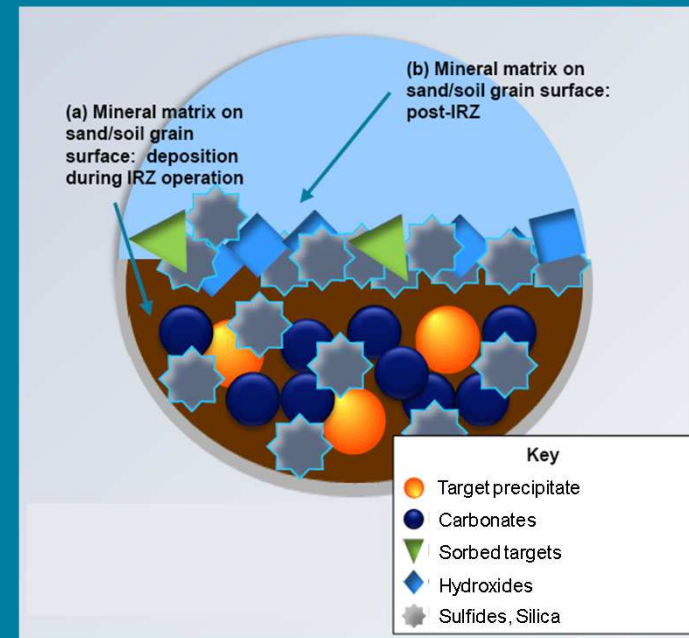
Why Does this Matter?



This conceptual understanding supports targeted treatment of plumes and provides a more reliable prediction on the relative benefits of partial active treatment

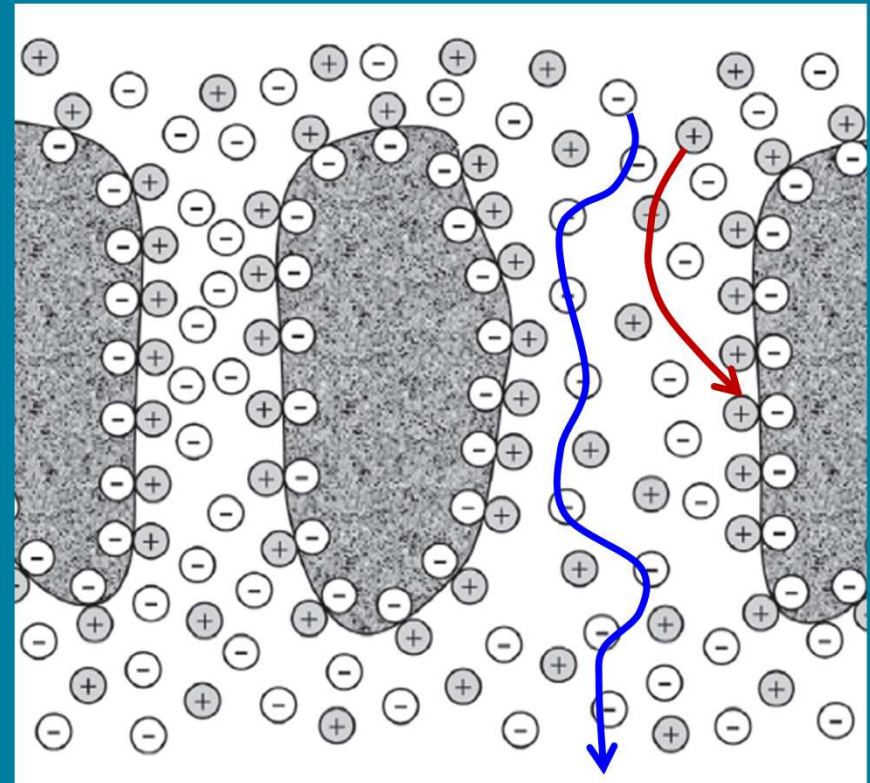
In Situ Treatment Approaches

- Leverage natural biological, geochemical, and hydrogeological processes to facilitate contaminant destruction or immobilization
- Often can provide sustained treatment performance years after short-term activity
- Targeted treatment results in reduced overall remediation timeframes
- Readily incorporated with other approaches
- 15+ years of successfully treating hydrocarbon and solvent plumes
- New technologies applicable for mining-related constituents



Example: Sulfate

- Common to mines targeting sulfidic ore bodies
 - Liberated during milling and in tailings management
- Mobile and creates large plumes
 - Natural attenuation may not be an option
- Microbially-mediated reduction to sulfide minerals and elemental sulfur
$$\text{SO}_4^{2-} \rightarrow \text{H}_2\text{S} + \text{HS}^-$$
- Precipitates are protected in a matrix of other minerals and remain sequestered

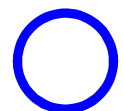




Reduction



Adsorption/co-precipitation/encapsulation



Sulfide



pH &/or Anion manipulation

1		2												13	14	15	16	17	18	
IA		IIA												IIIA	IVA	VA	VIA	VIIA	VIIIA	
New Original																				
Alkali metals		Alkaline earth metals																		
Actinide series		Transition metals																		
Poor metals		Nonmetals																		
Noble gases																				
Solid		Liquid																		
Gas																				
Synthetic																				
1	H	2	He											5	6	7	8	9	10	
Hydrogen	1.00794	Lithium	6.941											Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon	
3	Li	4	Be											13	14	15	16	17	18	
Sodium	22.989770	Magnesium	24.3050											Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon	
19	K	20	Ca	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
Potassium	39.0983	Calcium	40.078	Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton	
37	Rb	38	Sr	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	
Rubidium	85.4678	Strontium	87.62	Yttrium	Zirconium	Niobium	Molybdenum	Technetium	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon	
55	Cs	56	Ba	57 to 71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	
Cesium	132.90545	Barium	137.327		Hafnium	Tantalum	Tungsten	Rhenium	Osmium	Iridium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine	Radon	
87	Fr	88	Ra	89 to 103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	
Francium	(223)	Radium	(226)		Rutherfordium	Dubnium	Seaborgium	Bohrium	Hassium	Meitnerium	Darmstadtium	Roentgenium	Ununbium	Ununtrium	Ununquadium	Ununpentium	Ununhexium	Ununseptium	Ununoctium	

Atomic masses in parentheses are those of the most stable or common isotope.

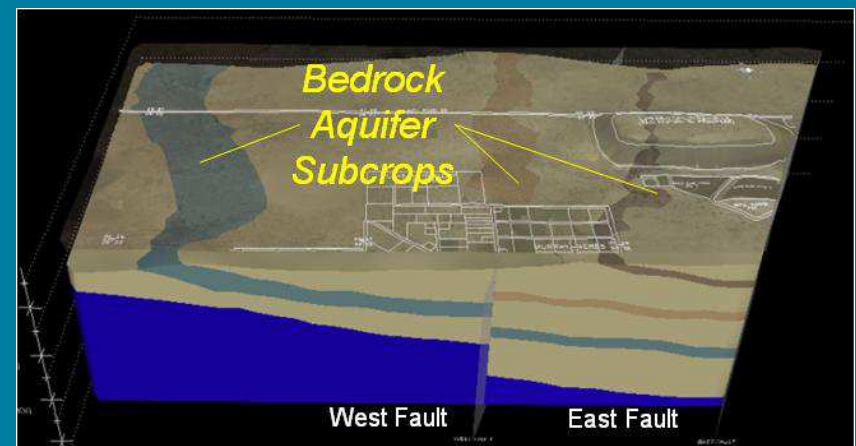
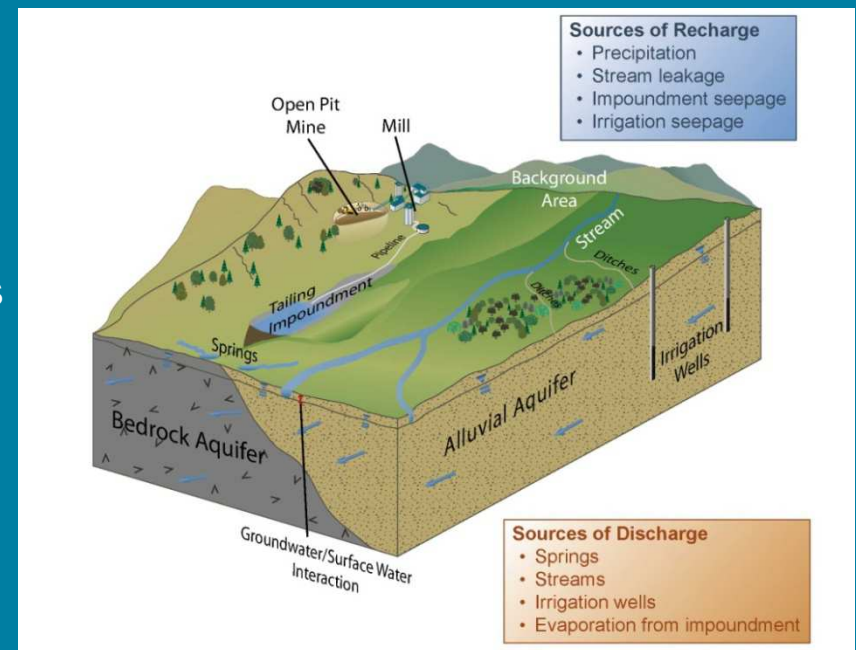
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Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

57 La Lanthanum 138.9055	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
89 Ac Actinium (227)	90 Th Thorium 232.0381	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (268)	102 No Nobelium (269)	103 Lr Lawrencium (262)

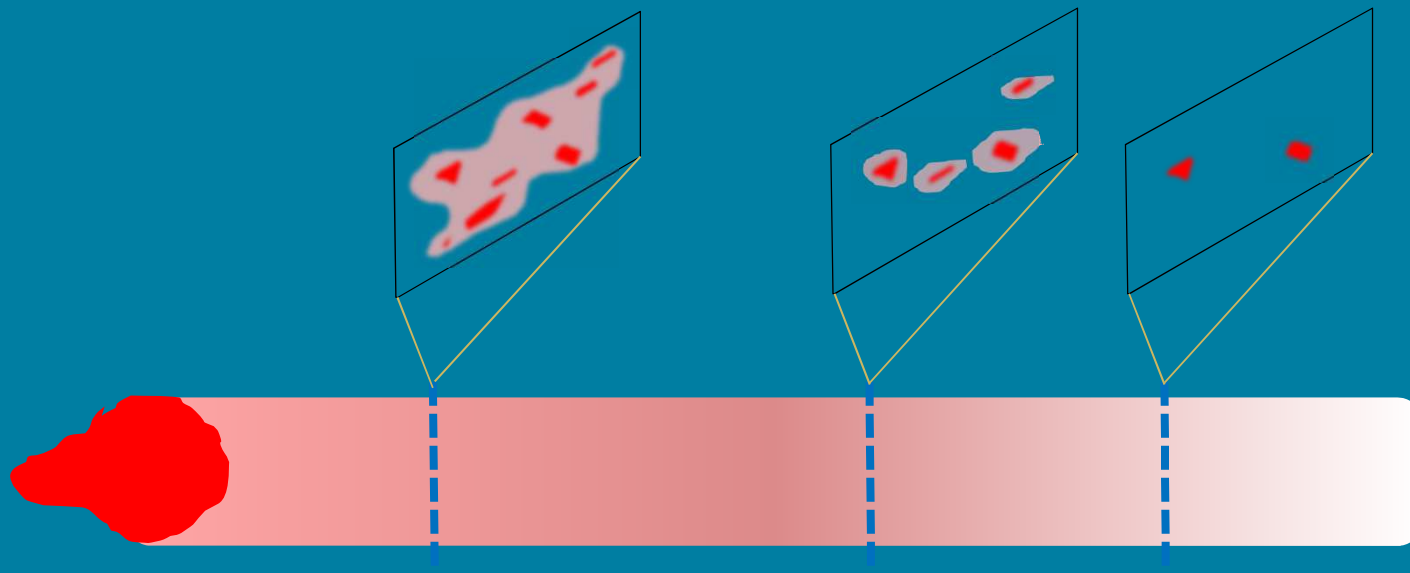
The “Hii” Road

- Holistic Viewpoint
 - Robust Conceptual Site Model
 - Avoid compartmentalization
 - Understand macro-scale interrelationships
 - Identify areas of maximum importance
- Integrated Development
 - Collaborate with mine personnel
 - Leverage work in one area to benefit another
- Incremental Implementation
 - Prioritize emphasis
 - Meaningful progress guided by observation
 - Adapt initial configurations in real time

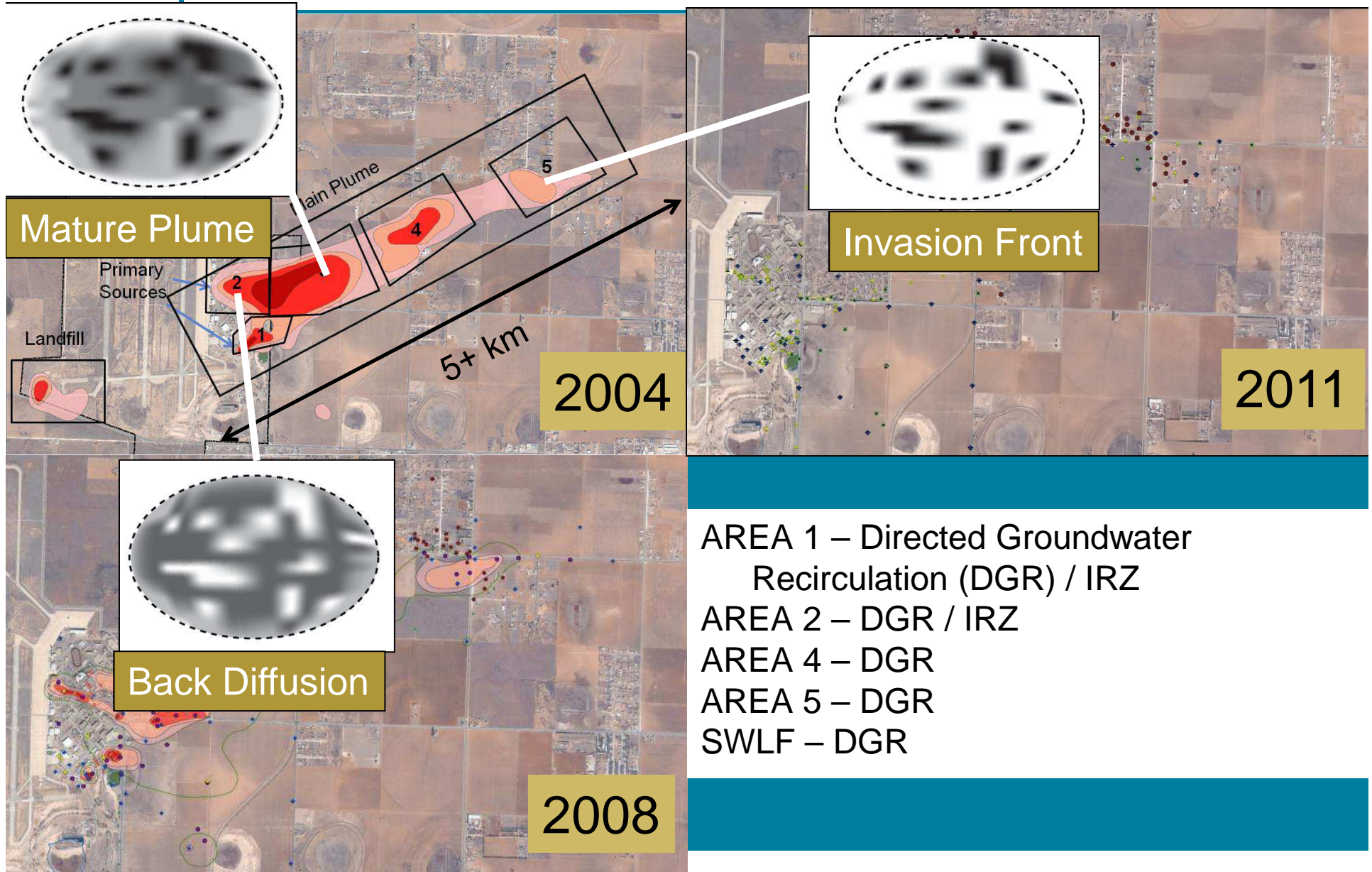


Why Does a Flux-Focused Approach Matter?

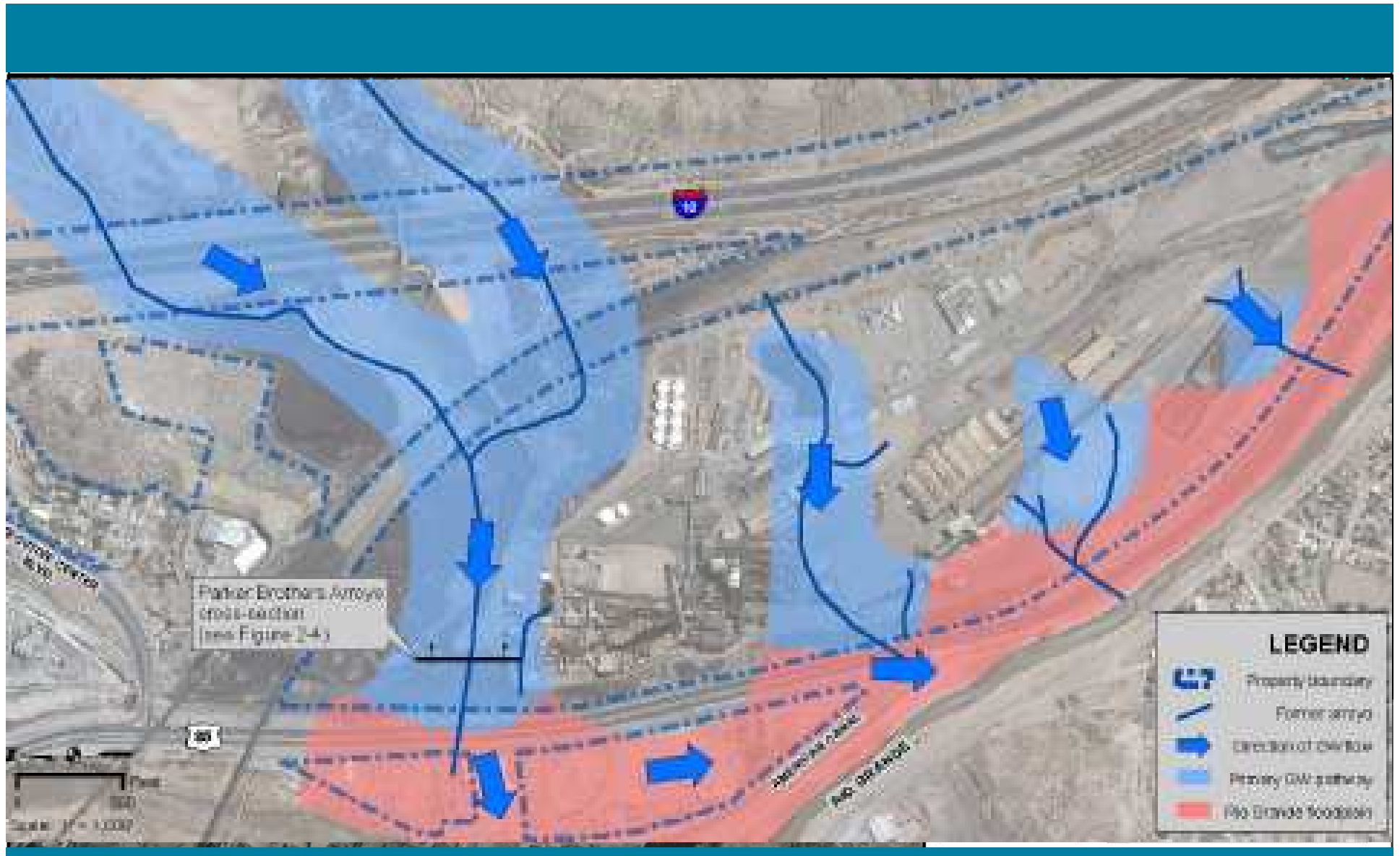
- Reality: 80% of flow occurs in 20% of the pore space
 - Not all pores are equal. Focus on the flux!
- Flux controls plume strength and risk
- Largest return by focusing on flux
- Partial source treatment meaningfully reduces risk
- Plume maturity impacts treatment performance



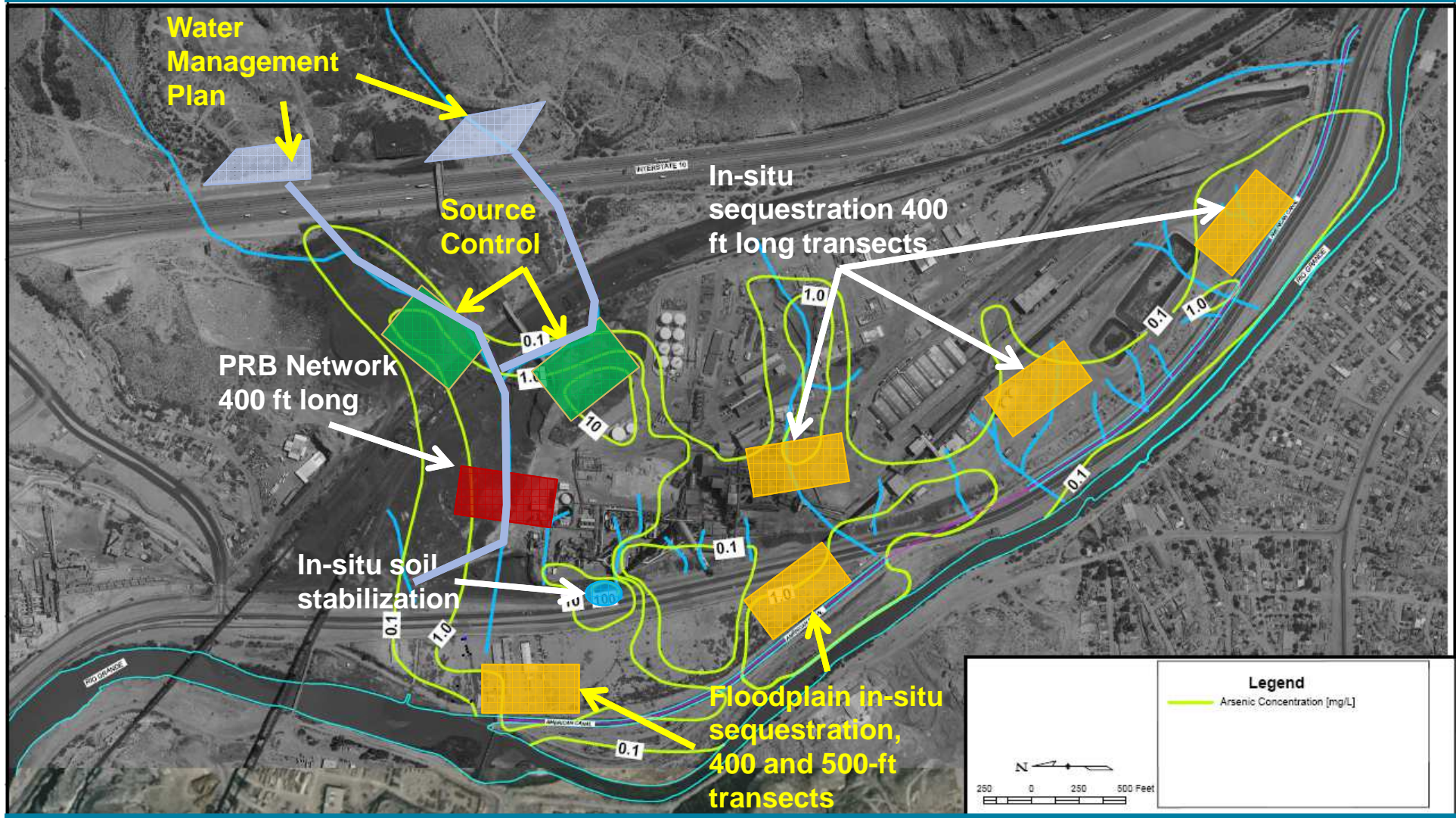
Example: Former Reece AFB



Example: Former ASARCO El Paso Smelter



Example: Former ASARCO El Paso Smelter



Conclusions

Technical advances in remediation hydrogeology and in situ treatment technologies can be leveraged to better address groundwater plumes at mine sites

A holistic and flux-focused approach will compress the overall life-cycle and result in near-term progress that reduces risk, supports an immediate reduction in reserves, and provides the backbone for a sustainable strategy





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